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Parametric Erosion Investigation (Propellant Adiabatic Flame Temperature)

by Paul J. Conroy, Paul Weinacht, and Michael J. Nusca

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Abstract

In this report, we investigate the influence of quasi-independent parameters and their potential influence on erosion in guns. Specifically, we examine the effects of flame temperature and the effect of assuming that the Lewis Number (ratio of mass to heat transport to the surface), Le, is one. The adiabatic flame temperature was reduced for a propellant through the addition of a diluent from a high of 3,843 K similar to that of M9 down to 3,004 K, which is near the value for M30A1 propellant. Mass fractions of critical species at the surface with and without the assumption of Le = 1 are presented, demonstrating that certain species preferentially reach the surface providing varied conditions for the surface reactions. The results for gun tube bore surface regression qualitatively agree with previous studies and with current experimental data. The propellant composition influence upon erosion must still be inferred at this time from the presence of specific product species at the surface because the finite-rate gas surface reactions are not well known under ballistic conditions.

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1. Introduction

The inner surfaces of most gun tubes regress as a result of various mechanisms, such as mechanical abrasion, pyrolysis, melting, spalling, and possibly others, when the gun is fired. Historically, the propellant adiabatic flame temperature (obtained from Gibbs free energy minimization with constant volume and no heat loss) has been considered to be the most important factor in determining erosivity [1–3]. Previous modeling and experimental efforts have not identified the fundamental cause of the erosion, and some discrepancies were found between flame-temperature correlations [3–5]; the discrepancies were not resolved. Attempts to model erosion using first principles have been and are currently being made [6–9], although it is believed that significant additional work is still required to understand the fundamental physics involved.

In this study, the influence of propellant flame temperature on erosion is analyzed as an initial step toward understanding the principle components of the erosion problem in a parametric fashion. The contributions due to mechanical wear and abrasion are not included in the study, nor are the effects of altered material composition on the surface. Instead, this study focuses on the surface thermochemical portion of erosion using full equilibrium thermochemistry, independent heat transport, and multicomponent species mass transport to the surface.

2. Erosion Model Description

Although described elsewhere [8, 9], for completeness, the basic outline and new additions to the U. S. Army Research Laboratory (ARL) erosion physics test model are elaborated upon here. The model consists of three fully coupled portions consisting of thermal ablation/heat transfer/conduction, mass transport, and thermochemistry. The code uses the gas-phase properties in the core flow of the gun tube from XKTC [10], and certain data from IBBLAKE [11–13]. The thermochemistry is assumed to be full-equilibrium chemistry and incorporates the NASA LEWIS [14] database. New additions to the model include:

(1) variable surface physical properties, conductivity k(T), and specific heat $C_p(T)$;

(2) surface material phase change from body-centered cubic (BCC) to face-centered cubic (FCC) (the material replenishment section recognizes the surface temperature and the correct phase);

(3) a user-defined "freeze-out" temperature that deactivates the surface chemistry;

(4) an iterative procedure that provides convergence for surface-control volume temperature (the gas and solid specific heats are temperature-dependant and require iteration for convergence); and

(5) all user-defined primary inputs (i.e., no hardwired inputs and case to case consistency).

The model considers both melting and pyrolysis from surface chemistry. Conceptually, as shown in Figure 1, the surface heats from convection until the chemical activation temperature is overcome. At this point, surface reactions are permitted to occur, releasing additional energy into the system as a source term at the surface and producing appropriate gaseous, solid, or liquid products. The reaction products can be either remain as some solid materials or be removed from the area as liquids or gases. The later case results in pyrolysis or ablation. As the surface regresses, the solids are refreshed accordingly.

The following assumptions have been made in the erosion model:

(1) one-dimensional (1-D) heat conduction,

(2) no subsurface chemical diffusion or reactions,

(3) instantaneous removal of all surface liquids and gas products,

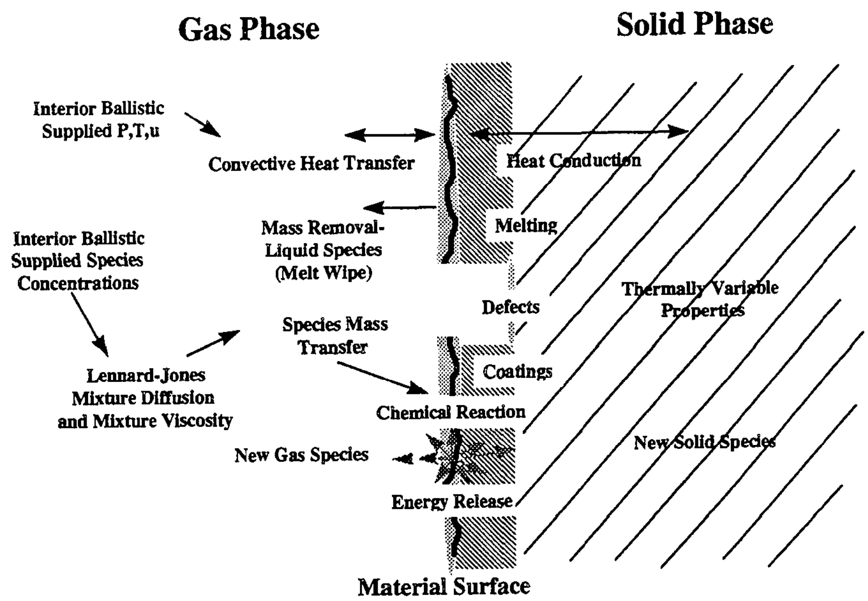

Figure 1. Conceptual Erosion Model Illustration.

(4) no feedback to the interior ballistics calculation in the core flow,

(5) release and treatment of chemical energy as a surface source term, and

(6) freezing of species (i.e., no chemical reactions) from the core flow to the wall.

The surface energy balance (when there is no melting) consists of the convective heat input to the surface, along with the possible contribution due to the surface reaction, shown in equation (1), where T is the wall temperature, k is the thermal conductivity, and h is the convection coefficient [15]. This source term is balanced with the energy conducted through the material:

$$h\left(T_{gas} - T_{wall}\right) = -k\frac{\partial T}{\partial r} - \text{Source}. \tag{1}$$

However, when the system is melting, the energy balance also includes the fixed-surface temperature condition (because the temperature cannot rise beyond this value as the material is removed as fast as it melts and additional energy is preferentially used for more phase transition), as well as the latent heat of formation of the molten material, as shown in equations (2) and (3):

$$T_{wall} = T_{melt} \,, \tag{2}$$

and

$$\rho L \frac{\partial s}{\partial t} = h\left(T_{gas} - T_{wall} \right) + k \frac{\partial T}{\partial r} + \text{Source}. \tag{3}$$

In equation (3), L is the latent heat of formation, ρ is the density of the surface material, and s represents the instantaneous surface location that must be iterated upon for convergence until the energy balance is satisfied.

3. Calculation Methodology for Flame-Temperature Study

The calculations presented in this study were initiated with a BLAKE calculation of a notional propellant having an adiabatic flame temperature of 3,843 k. This particular baseline propellant (an altered JA2) was chosen because it had an exceptionally high adiabatic flame temperature, as well as it previously experimentally demonstrated erosivity [9]. The basic charge configuration had a notional slab geometry. The propellant flame temperature was reduced from the nominal value by adding a diluent (N_2) to the nominal gas mixture in increasing mass percentages of 15%, 30%, and 60%, without reducing the other components' mass fractions. As a result, the final percentage of diluent added was somewhat less than stated previously, as shown in Table 1.

Using these formulations for the propellants with reduced flame temperature, ranging from 3,843 K down to 3,004 K, iterations were then performed for the XKTC calculations, which involved altering the propellant mass and web, such that the projectile muzzle velocity, muzzle energy, and the peak pressure in the gun were held constant for all four scenarios. The results were used in the IBBLAKE calculations. These calculations involved many iterations in order to determine the

Table 1. Calculation Matrix to Investigate the Effect of Flame Temperature

M256[a] With a 3.629-kg Projectile (% N_2)	Muzzle Velocity (m/s)	Peak Pressure (MPa)	Propellant Mass (kg)	Mole (% Carbon)	Mole (% Hydrogen)	Mole (% Oxygen)	Mole (% Nitrogen)	Adiabatic Flame Temperature (K)
RPD 351 Nominal	1537.0	453.0	6.074	19.694	27.406	40.794	11.932	3,843
+15	1544.1	451.9	6.346	17.634	24.539	36.526	21.145	3,603
+30	1542.2	453.4	6.623	15.964	22.215	33.067	28.613	3,384
+60	1538.9	456.7	8.165	13.422	18.677	27.801	39.981	3,004

[a] Assumed nonchromium electroplated M256 tank cannon.

combination of projectile mass, propellant mass, and web size which produced the desired results, while maintaining a burn-out condition at projectile exit. Although the total charge mass is changed for each permutation (see Table 1) an attempt is made to account for this effect later when presenting the results.

The resulting information involving the gun tube core flow gas composition, temperature, pressure, and velocity for the four different scenarios was then used as input for the calculations; the results of which are discussed in section 4.

4. Results

Shown in Figures 2–5 are gun tube, inner-surface temperatures for three of the four notional propellant formulations (Table 1) at three axial locations along the gun tube wall, measured from the rear face of the tube: 635 mm; 686 mm; and 1,040 mm. The initial location of the base of the projectile is 559 mm. The flat areas at the top of the curves in Figures 2–4 are due to the surface temperature reaching a user-defined, surface melt temperature. What is seen in this data is the general reduction from the high, overall temperatures in Figure 2 to the lower temperatures in Figure 5. Note that Figures 2–4 reflect the time at which the surface remains at the melt temperature. Therefore, the larger these regions are, the more time the surface remained at the melt temperature and, thus, the more material was removed. However, for the propellant with the lowest adiabatic flame temperature of 3,004 K, the gun tube, inner-surface temperatures do not reach the melting temperature at any axial location in Figure 5, while, for the charge containing the propellant with the adiabatic flame temperature of 3,384 K (shown in Figure 4), only one axial location reaches the melting temperature. The two higher adiabatic flame temperature of 3,843 K and 3,603 K exhibit melting at two of the three chosen axial locations in Figures 2 and 3.

Figure 6 integrates the total mass loss over time for the three propellants with the higher flame temperatures. The slight increase in the recession in Figure 6 before 3.5 ms and after 4.5 ms in the curves is due to the pyrolysis, which is also included in the total mass loss and intended for a follow-on study.

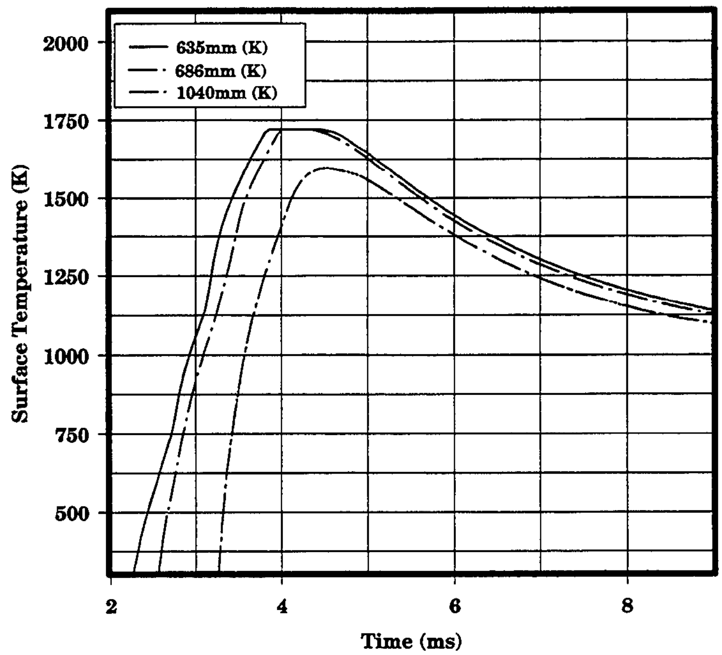

Figure 2. Gun Tube Surface Temperatures for Three Axial Locations and a Single Firing of a Charge Having a Propellant Adiabatic Flame Temperature of 3,843 K.

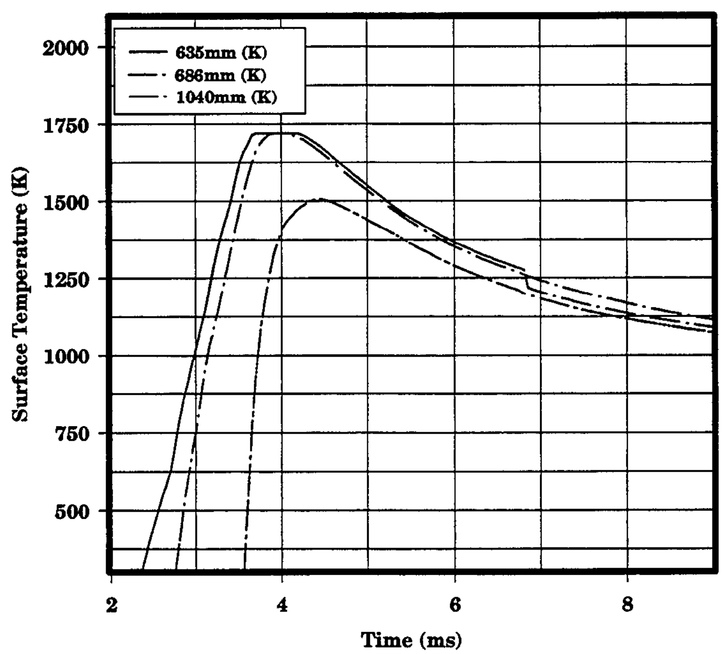

Figure 3. Gun Tube Surface Temperatures for Three Axial Locations and a Single Firing of a Charge Having a Propellant Adiabatic Flame Temperature of 3,603 K.

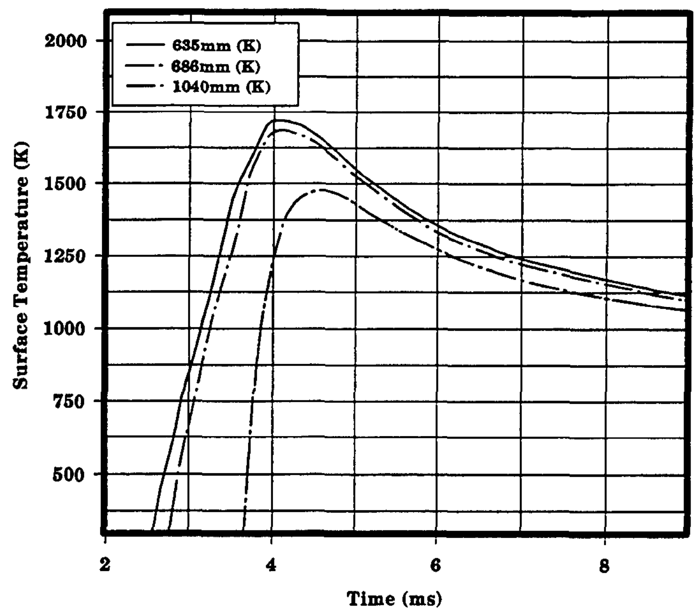

Figure 4. Gun Tube Surface Temperatures for Three Axial Locations and a Single Firing of a Charge Having a Propellant Adiabatic Flame Temperature of 3,384 K.

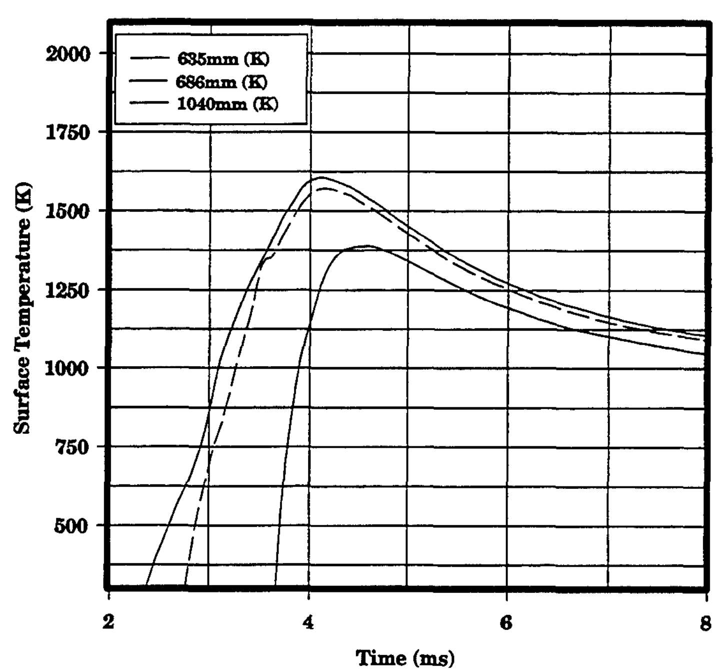

Figure 5. Gun Tube Surface Temperatures for Three Axial Locations and a Single Firing of a Charge Having a Propellant Adiabatic Flame Temperature of 3,004 K.

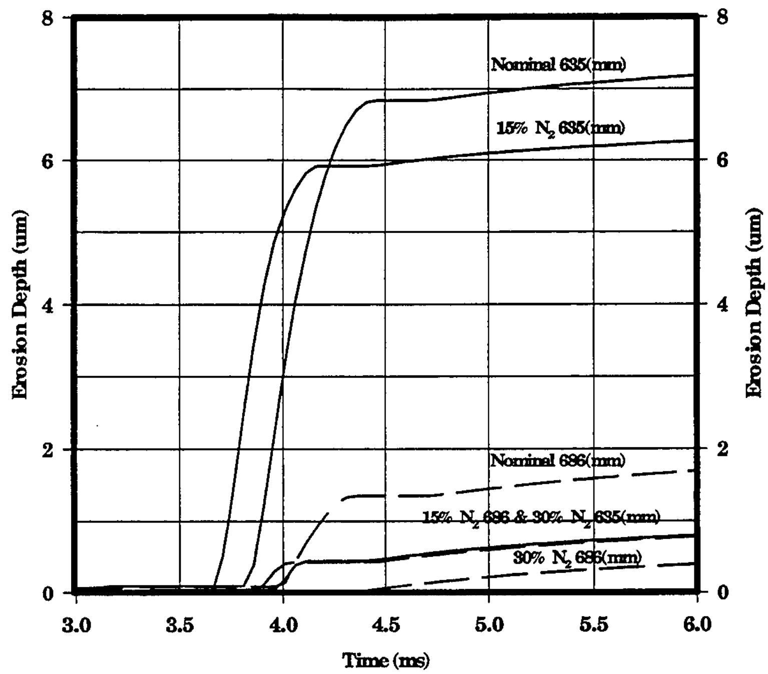

Figure 6. Computed Single-Shot Erosion Depths vs. Time for Propellant Flame Temperatures of 3,843 K; 3,603 K; and 3,384 K at Three Axial Locations Each.

In Figure 7, both experimental and numerical data are presented as normalized erosion (surface regression) vs. adiabatic flame temperature. The experimental data include some data from a study presented by Ahmad [16] concerning 5-in/54 gun tube erosion data, as well as Kruczynski's [17] M199 M203A1 origin of rifling wear data per round and the original version of the M919 25-mm-round average wear per round at the origin of rifling [18]. Ahmad's data include two different experimental data sets for a 5-in/54 system. The values with higher erosion are for a series of firings without coolant additives in the charge, while a series presented with lower erosive values included a talc wax liner in the charges to reduce the overall heat transported to the gun tube wall. Kruczynski's data include both horizontal and vertical wear at the origin of rifling to account for the asymmetrical wear pattern seen in some artillery charges; however, both points are practically coincidental for this plot, including values not shown for the M203 charge.

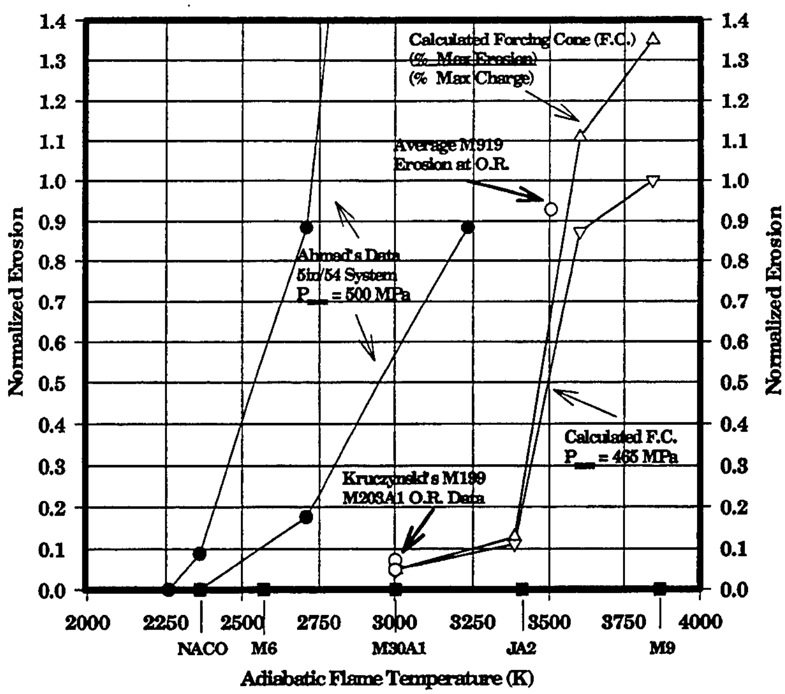

Figure 7. Computed and Experimental Normalized Erosion per Round vs. Adiabatic Flame Temperature. The Numerical Calculations Are Also Normalized for Charge Mass Effects. The Adiabatic Flame Temperature for Various Propellants Is Shown for Reference.

The computed numerical data shown in Figure 7 consist of two curves of four points each and are plotted as triangles. Both curves have been normalized to the maximum amount of computed wear occuring at the 635-mm axial location. The lower of the two curves reflects this normalization by having 1.0 as the maximum value of regression. This computed data was then renormalized to incorporate the maximum charge mass, as well as the maximum surface regression (percent maximum erosion/percent maximum charge), which resulted in the slightly higher plot. The general trend and values of erosivity vs. adiabatic flame temperature seems to be reasonable when compared to the experimental data presented for the 155-mm and 25-mm guns, which has also been normalized for regression.

While the general regression trend and shape holds for the data of Ahmad [16], the values appear to be inexplicably shifted in temperature by about 700 K, possibly due to the fact the Ahmad was firing experimental charges. An interesting note in Figure 7 is that, even though no melting occurred for the propellant having the adiabatic flame temperature very close to that of M30A1, the computed surface regression was about that seen by Kruczynski [17] who was firing M30A1 propellant. These pyrolization products and related effects, as was stated, are an area of a follow-on study that will investigate the products that the equilibrium chemistry calculation indicates and what actually is being removed from the surface.

The photo of a 155-mm-howitzer origin of rifling in Figure 8 shows what type of erosion or pyrolization can occur at the origin of rifling. This photograph shows evidence of heat checking, cracking, and loss of lands; however, there is no obvious evidence of surface melting of this scale as the calculations predicted. Nonetheless, the situation is quite different for the M256 chromed gun tube shown in Figure 9, which fired JA2-type propellants. Evidence of chrome removal, surface pitting, and melting are all present in this photograph, as was also expected from the calculations.

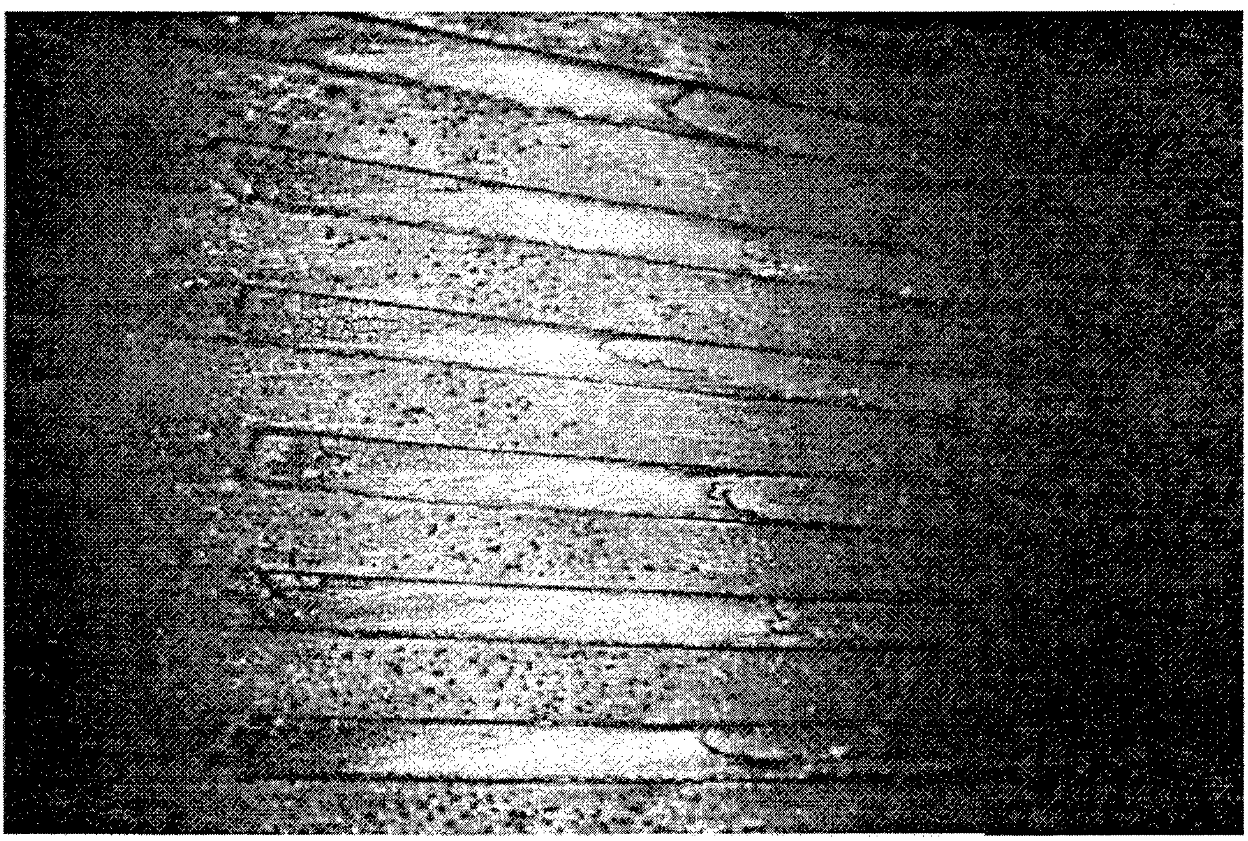

Figure 8. 155-mm Howitzer Origin of Rifling Showing Pyrolysis, Loss of Chrome, and Rifling Degradation [17].

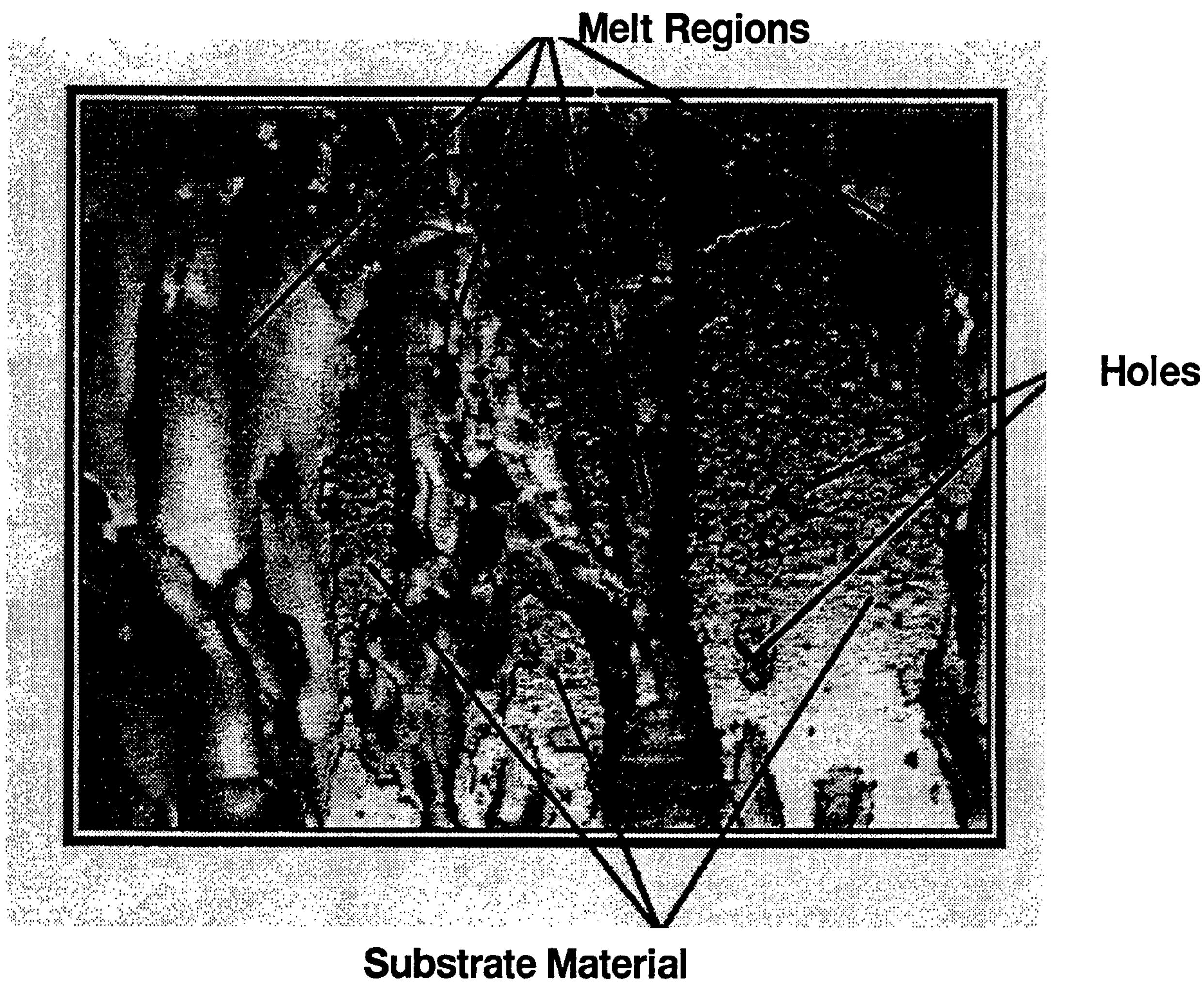

Figure 9. 120-mm M256 Tank Cannon Surface at Forcing Cone Showing Chrome Stripping, Pits, and Melt Regions [25].

Propellant combustion, product species, and molar concentrations are presented in Figures 10 and 11. The differences between the core flow product species in Figure 10 and the wall surface product species in Figure 11 are illustrative of the effect of multicomponent mass transport upon the species concentration at the surface. The species principally affected using nominal propellant by the mass transport are CO and CO_2. The concentrations in the core flow appear to contain less CO and more CO_2 than at the wall, where the concentration of CO rises and that of CO_2 is less. The CO/CO_2 varies approximately 15% between these regions. This ratio is thought to be very important [1, 19–24]. Fundamental studies are underway to investigate mechanisms in which free carbon may

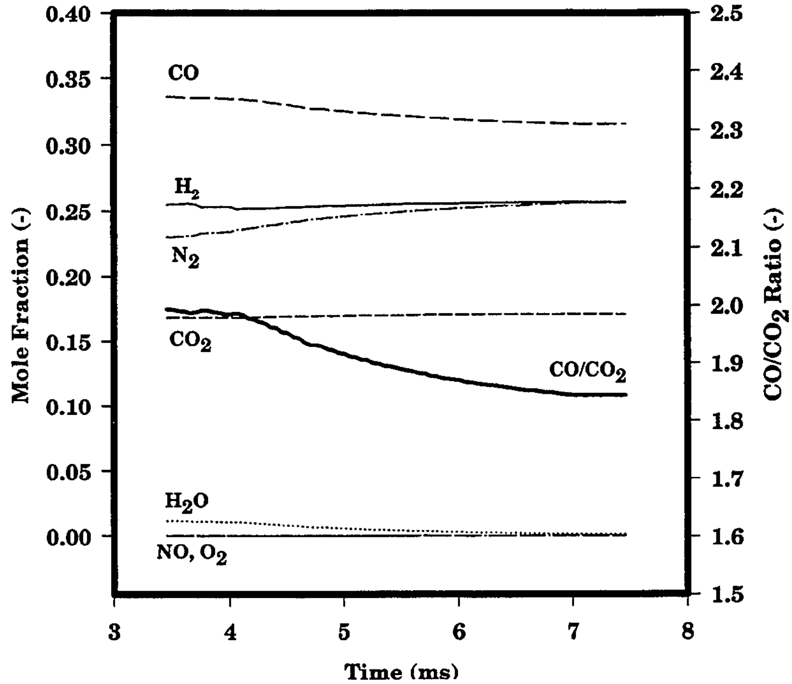

Figure 10. Selected Product Species Mole Fractions and the CO/CO_2 Ratio for the Gun Tube Core Flow.

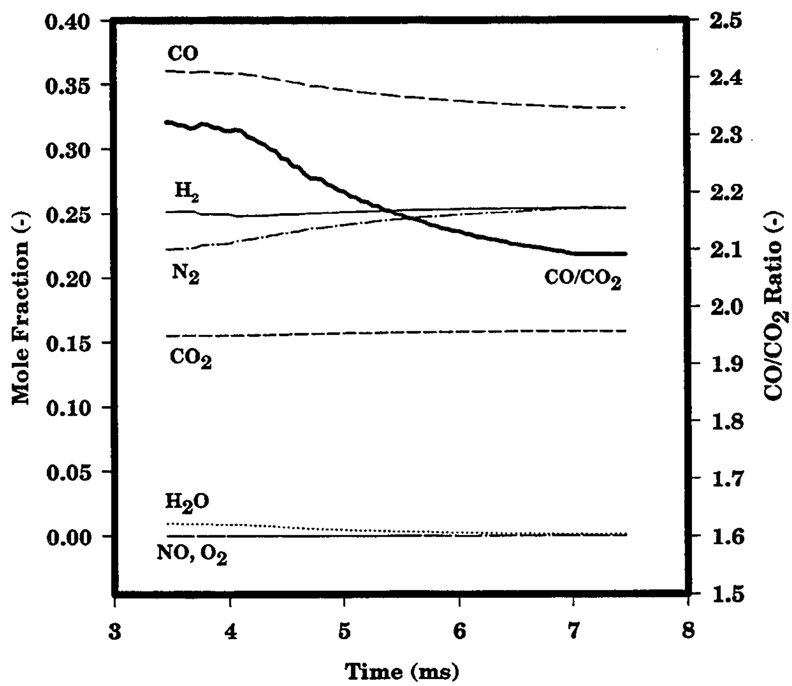

Figure 11. Selected Product Species Mole Fractions and the CO/CO_2 Ratio for the Gun Tube Surface.

be formed from either CO or CO_2 [24]. Eventually, the primary surface reactions and rates will be known and included in the surface reaction models. The proper state and species concentrations will be required to provide results based on experimentally validated physical processes.

5. Conclusions

Flame-temperature effects on erosion have been studied with four notional computational charges with the assumed gun tube properties for an M256 nonelectroplated cannon. These four notional charges had propellant adiabatic flame temperatures of 3,843 K; 3,603 K; 3,384 K; and 3,004 K. While the trends in erosion match those seen previously of Ahmad, the actual values agree better with recent system data, specifically, recently measured data from the 155-mm M203A1 charge and 25-mm M919 round erosion.

Differences in species concentrations exist between the core flow and wall region. This difference may be critical in providing the correct input for chemical reactions at the surface, but, as of yet, the actual mechanisms of erosion at the surface remain unknown.

Further parametric investigations of this type are needed in order to provide an understanding of the interactions of the thermal and chemical, with the ultimate inclusion of mechanical, components as well to erosion/wear. Also, this type of investigation provides guidance for further fundamental studies.

6. References

1. Fisher, E. B. "Heating and Wear Environment." *Proceedings of the U.S. Army Research Laboratory Sagamore Workshop on Gun Tube Heating and Erosion*, July 1996.

2. Caveny, L. H. "Steel Erosion Produced by Double Base, Triple Base, and RDX Composite Propellants of Various Flame Temperatures." ARLCB-CR-80016, U.S. Army Armament Research and Development Center, October 1980.

3. Lawton, B. "Thermal and Chemical Effects on Gun Barrel Wear." *Proceedings of the 8th International Symposium on Ballistics*, vol. 2, pp. 27–36, Orlando, FL, October 1984.

4. Watervliet Arsenal. *Proceedings of the Interservice Technical Meeting on: Gun Tube Erosion and Control.* Watervliet, NY, 25–26 February 1970.

5. U.S. Army Armament Research and Development Center. *Proceedings of the Tri-Service Gun Tube Wear and Erosion Symposium.* Dover, NJ, March 1977.

6. Evans, M. R. "User's Manual for Transient Boundary Layer Integral Matrix Procedure TBLIMP." Aerotherm UM-74-55, October 1974.

7. Dunn, S., D. Coates, G. Nickerson, S. Sopok, P. O'Hara, and G. A. Pflegl. "Unified Computer Model for Predicting Thermochemical Erosion in Gun Barrels." AIAA 95-2440, *Proceedings of 31st AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit*, July 1995.

8. Weinacht, P., and P. J. Conroy. "A Numerical Method for Predicting Thermal Erosion in Gun Tubes." ARL-TR-1156, U.S. Army Research Laboratory, Aberdeen Proving Ground, MD, July 1996.

9. Conroy, P. J., P. Weinacht, and M. J. Nusca. "Surface Chemistry Effects on High Performance Tank Ammunition." ARL-TR-1526, U.S. Army Research Laboratory, Aberdeen Proving Ground, MD, October 1997.

10. Gough, P. S. "The XNOVAKTC Code." BRL-CR-627, U.S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, MD, February 1990.

11. Freedman, E. "BLAKE - A Thermodynamic Code Based on Tiger: Users' Guide and Manual." ARBRL-TR-02411, U.S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, MD, July 1982.

12. Anderson, R. D., and K. D. Fickie. "IBHVG2 - A Users Guide." BRL-TR-2829, U.S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, MD, July 1987.

13. Janke, P. J., J. A. Dyvik, and C. L. Marksberry. "Electrothermo-Chemical Propellant Extensions to the IBHVG2 Interior Ballistics Simulation: Model Development and Validation." CPIA Publication 620, vol. 3, pp. 171–181, October 1994.

14. Gordon, S., and B. J. McBride. "Computer Program for Calculation of Complex Chemical Equilibrium Compositions, Rocket Performance, Incident and Reflected Shocks, and Chapman-Jouget Detonations." NASA SP-273, NASA LEWIS, OH, 1971.

15. Conroy, P. J. "Gun Tube Heating." BRL-TR-3300, U. S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, MD, December 1991.

16. Ahmad, I. "The Problem of Gun Barrel Erosion: An Overview." *Gun Propulsion Technology,* vol. 109, chap. 10, 1988.

17. Kruczynski, D. L., I. C. Stobie, and M. B. Kummerich. "Gun Tube/Charge/Projectile Interactions and Gun Tube Wear." BRL-TR 3004, U.S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, MD, June 1989.

18. Talley, J. Q., and J. A. Owczarczak. "25-mm Barrel Erosivity Study." Final Report Prepared for GenCorp Aerojet Corporation, Aerojet Ordnance Division, Downey, CA, August 1991.

19. Kamdar, M. H., and J. D. Venables. "Characterization of Surface Layers in Gun Barrels." ARLCB-TR-84041, U.S. Army Armament Research and Development Center, Watervliet, NY 1984.

20. Morphy, C. C., and E. B. Fisher. "The Role of Carburization in Gun Barrel Erosion and Cracking." ARBRL-CR-00459, U.S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, MD, July 1981.

21. Morphy, C. C., and E. B. Fisher. "Gas Chemistry Effects on Gun Barrel Erosion: a Shock Tube Investigation." ARBRL-CR-00481, U.S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, MD, June 1982.

22. Ringers, D. A., and J. B. Danese, Jr. "Quantum Chemistry, Chemisorption, and Erosion I. Properties of Diatomic Molecules." BRL-TR-2023, U. S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, MD 1977.

23. Weigand, J. H. "The Application of Erosion in Vent Plugs to Recoiless Guns." BRL-MR-340, U.S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, MD 1945.

24. Chabalowski, C. Personal communication. U. S. Army Research Laboratory, Aberdeen Proving Ground, MD 1997.

25. Bundy, M. Personal communication. U.S. Army Research Laboratory, Aberdeen Proving Ground, MD, 1993.

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In this report, we investigate the influence of quasi-independent parameters and their potential influence on erosion in guns. Specifically, we examine the effects of flame temperature and the effect of assuming that the Lewis Number (ratio of mass to heat transport to the surface), Le, is one. The adiabatic flame temperature was reduced for a propellant through the addition of a diluent from a high of 3,843 K similar to that of M9 down to 3,004 K, which is near the value for M30A1 propellant. Also shown are mass fractions of critical species at the surface with and without the assumption of Le = 1, demonstrating that certain species preferentially reach the surface providing varied conditions for the surface reactions. The results for gun tube bore surface regression qualitatively agree with previous studies and with current experimental data. The propellant composition influence upon erosion must still be inferred at this time from the presence of specific product species at the surface because the finite-rate gas surface reactions are not well known under ballistic conditions.

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